

Limiting First Order Phase Transitions in Dark Gauge Sectors from Gravitational Waves experiments

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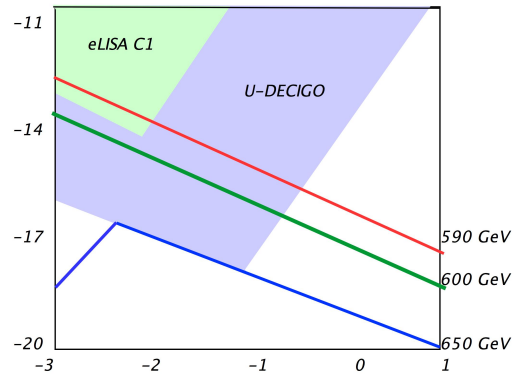
We discuss the possibility to indirectly test First Order Phase Transitions of hidden sectors. We study the interesting example of a *dark standard model* with a deformed parameter space in the Higgs potential. A dark electroweak phase transition can be limited from next future experiments like eLISA and DECIGO.

I. INTRODUCTION

A new era of astrophysics and cosmology was opened with the detection of gravitational waves. For the first time, we have a chance to explore the dark side of the Universe from gravitational radiation. The possibility to test new physics beyond the standard model of particles is particularly exciting. For instance, it is conceivable that gravitational wave detectors could constrain or detect signals from unconventional candidates of dark matter beyond WIMP paradigm¹. For instance, if dark matter is composed by particles from a dark gauge sector, a dark first order phase transition in the early Universe will still be an open possibility. In this letter, we suggest to test first order phase transitions from hidden gauge sectors with gravitational wave detectors. In particular, we will focalize our analysis to the case of a Dark Standard Model: $G_{SM} \times G'_{SM} \times Z_2$, where Z_2 is a discrete symmetry guaranteeing that matter and gauge content, Yukawa and gauge couplings of the dark SM (D-SM) are all equal to ordinary SM (O-SM) ones, i.e. $Z_2 : G_{SM} \leftrightarrow G'_{SM}$. The idea of Dark Matter as a specular hidden standard model was largely explored in literature and it has many interesting consequences in astrophysics and cosmology, Dark Matter Direct Detection, Ultra Cold Neutrons and Neutrino physics [7–24]². The Z_2 -symmetry can guarantee the specularity of O-SM and D-SM only at perturbative level. However, the Higgs potentials could receive extra non-perturbative self-interaction corrections from various unspecified dynamical mechanisms. So that, the D-SM Higgs, dub H' can have the same perturbative terms of O-SM Higgs H , as $\mu^2|H'|^2 + \frac{\lambda}{4}|H'|^4$, plus extra non-perturbative terms like $|H'|^6/\Lambda^2$. These extra terms can be particularly interesting in our case because they can lower the double well barrier. As a consequence, during the dark electroweak phase transition

at $T' \sim v \sim 200$ GeV, the materialization of Bubbles is particularly efficient and their collisions generate detectable gravitational signals. For instance, this mechanism could explain the dark matter genesis through a dark electroweak baryogenesis mechanism³. However, for a good satisfaction of Sakharov's criterions, an extra source of CP violating phases have to be introduced in the dark SM. For example, one can extend the minimal standard Model Higgs sector with a Higgs doublet $H_{1,2}$ and consequently $H'_{1,2}$. In this framework a CP violation in the D-SM can be introduced with a phase field which changes of a finite $\Delta\theta' \neq 0$ during the transition from a false to the true vacuum. A Dark electroweak baryogenesis, induced by D-SM particle scatterings on Bubbles with a CP-violating phase field localized on it, can be related to a production of gravitational wave signals from Bubble-Bubble collisions.

FIG. 1. GW spectra $h^2\Omega_{GW}$ as function of GW frequency is displayed in scale log-log scale ($\log_{10}(f[Hz]), \log_{10}(h^2\Omega_{GW}^2)$) for various non-perturbative scales $\Lambda = 590, 600, 650$ GeV, (conventionally) assuming $(\kappa_1 + \kappa_3) = 1$, $(\kappa_2 + \kappa_3) = 1$, $(\kappa_2 + \kappa_4) = 1$. In Green and Blue, we display the approximated expected experimental sensitivity of future GW interferometers eLISA C1 [34] and U-DECIGO [35] respectively.



We will show that for $v \geq \Lambda \geq 1$, TeV, the predicted signal can be detected by future experiments like eLISA

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¹ We mention that other interesting possibilities of GW emissions from collisions of bubbles were recently suggested [1–6].

² An alternative can be to introduce a dark strong sector with a low scale confinement, accounting for the correct abundance of dark matter and dark energy [25, 26]. Another interesting alternative was discussed in Ref.[27], where a hidden Born-Infeld condensate could generate a cosmological term as well as a neutrino mass and cold dark matter as a neutrino superfluid state.

³ For complete reviews on electroweak baryogenesis models see Refs.[28, 29].

(C1) and U-DECIGO. This letter is organized as follows: In Section II we will introduce the full Higgs sector of our model, in Section III we will discuss an example of electroweak baryogenesis mechanism and gravitational signals from Bubbles collisions. In Section IV we show our conclusions and comments on possible extensions and UV completions of our model.

II. MODEL

The O- and D- Higgs sector has a general potential which reads as

$$V_{(0)}^{TOT} = V_{(0)} + V'_{(0)} + V_{(0)}^{mix} \quad (1)$$

$$V_{(0)} = V_{(0)}^P + V_{(0)}^{NP}$$

$$V'_{(0)} = V'_{(0)}^P + V'_{(0)}^{NP}$$

$$V_{(0)}^{mix} = V_{(0)}^{mix,P} + V_{(0)}^{mix,NP}$$

where perturbative terms are

$$V_{(0)}^P = -\mu_i^2 H_i^\dagger H_i + \lambda_i (H_i^\dagger H_i)^2 + \lambda (H_i H_j)^\dagger (H_i H_j) \quad (2)$$

$$V'_{(0)}^P = -\mu_i^2 H_i'^\dagger H_i' + \lambda_i (H_i'^\dagger H_i')^2 + \lambda (H_i' H_j')^\dagger (H_i' H_j') \quad (3)$$

where $\lambda (H_i H_j)^\dagger (H_i H_j)$ and its mirror twin we mean to include $H_1^\dagger H_1 H_2^\dagger H_2$, $H_1^\dagger H_2 H_1^\dagger H_2$ and $h.c.$;

$$V_{(0)}^{mix,P} = -\bar{\kappa} (H_1 H_2)^\dagger (H_1' H_2') + h.c. \quad (4)$$

We assume that the only relevant non perturbative terms are D-ones:

$$V_{(0)}^{NP} = \frac{\kappa_1}{8\Lambda^2} (H_i' H_i'^\dagger)^3 + \frac{\kappa_2}{8\Lambda^2} (H_i' H_j')^3 \quad (5)$$

$$+ \frac{\kappa_3}{8\Lambda^2} H_i' H_i'^\dagger (H_j' H_j'^\dagger)^2 + \frac{\kappa_4}{8\Lambda^2} (H_i' H_i'^\dagger) (H_i' H_j')^2 + h.c.$$

with $i \neq j$ and $i, j = 1, 2$, where $\bar{\kappa} < 10^{-8}$ in order to avoid a dangerous thermalization among the O- and D- SM, where $\kappa_{1,...,4}$ parametrize the difference between the Non perturbative scale in Eq.(5) (See Ref.[14] for a complete discussion on reheating limits).

In thermal bath, the finite-temperature effective potential up to one-loop is

$$V^{(eff)} = V^{(0)} + V^{(1)}(T' = 0) + \Delta V^{(1)}(T') \quad (6)$$

which for $V^{(1)}(T' = 0)$ is the Coleman-Weinberg potential while $V^{(1)}(T')$ are thermal corrections.

$$V^{(1)}(T' = 0) \simeq \frac{c_i}{2} H_i'^\dagger H_i' \quad (7)$$

where

$$c_1 = +c_{H_1} + \frac{1}{4} y_t^2 + \frac{1}{16} (g_Y^2 + 3g_2^2) \quad (8)$$

$$c_2 = +c_{H_2} + \frac{1}{4} y_b^2 + \frac{1}{12} y_\tau^2 + \frac{1}{16} (g_Y^2 + 3g_2^2) \quad (9)$$

$$c_{H_i} = c_{H_i}^P - \frac{3}{4} c_{H_i}^{NP}$$

$$c_{H_i}^P = \frac{1}{2} \lambda_i + \frac{1}{4} \lambda + \frac{1}{12} \lambda_S$$

$$c_{H_1}^{NP} = \frac{1}{\Lambda^2} ((\kappa_1 + \kappa_3) v_1^2 + (\kappa_3 + \kappa_4) v_2^2)$$

$$c_{H_2}^{NP} = \frac{1}{\Lambda^2} ((\kappa_2 + \kappa_3) v_2^2 + (\kappa_3 + \kappa_4) v_1^2)$$

while thermal field theory corrections are understood and taken into account in the following section.

III. DARK ELECTROWEAK BARYOGENESIS AND GRAVITATIONAL WAVES

For the Dark Electroweak Baryogenesis, a double-well (or multiple) potential between a metastable false vacuum and the true (or lower) one is postulated. The quantum tunneling process, mediated by a Coleman-De Luccia-like instanton, sources the materialization of a true vacuum bubble. The quantum tunneling probability nearby the dark electroweak scale v_D is $O(1)$. In other words, $\Gamma(T'^*) \simeq H^4(T'^*)$, where T'^* is the critical phase transition temperature, $\Gamma(T')$ is the tunneling transition rate and H is the Hubble parameter. The three-dimensional Euclidean action of the Bubble is

$$S_3 = \int d^3r \left[\frac{1}{2} (\nabla H_i')^2 + V_{eff}(H_i', T') \right] \quad (10)$$

The proprieties of bubbles are parametrized by

$$\alpha = \frac{\epsilon(T'_*)}{\rho_{rad}(T')} \quad (11)$$

where

$$\epsilon(T') = \left[T' \frac{dV_{eff}^{min}}{dT'} - V_{eff}^{min}(T') \right]_{T'=T'_*} \quad (12)$$

α is the ratio of the false vacuum energy density on the plasma thermal energy density

$$\rho_{rad}^D(T') = \frac{\pi^2}{30} g_*(T') T'^4 \quad (13)$$

In the Dark Electroweak Baryogenesis, the CP and B-violations are induced from scatterings of SM particles on bubbles. The O- and D- Higgs minima are

$$H_i = \frac{1}{\sqrt{2}} \left(0, \frac{v_i}{\sqrt{2}} e^{i\theta_i} \right), \quad H'_i = \frac{1}{\sqrt{2}} \left(0, \frac{v'_i}{\sqrt{2}} e^{i\theta'_i} \right) \quad (14)$$

If $\theta'_1 \neq \theta'_2$, CP-violating phases are introduced in the Yukawa couplings as $\theta' = \theta'_1 - \theta'_2$. In particular, in couplings with quarks introduce a CP-violating phase in the CKM matrix as

$$\mathcal{L}_{U',D',H'_{1,2}} \rightarrow v_1 Y_{U,gg'} e^{i\theta'_1} \bar{Q}'_{L,g} U'_{R,g'} + Y_{D,gg'} v_2 e^{i\theta'_2} \bar{Q}'_{L,g} D'_{R,g'} + h.c. \quad (15)$$

where g, g' are quark generations.

In the limit of $\bar{\kappa} \rightarrow 0$ (O- and D-Higgs decoupling), the Lagrangian for a Dark fermion ψ' in the background of a bubble wall with a CP-odd θ' field localized on it

$$\mathcal{L} = i\bar{\psi}' \left(\partial_\mu + im_{\psi'} + \frac{i}{2} \frac{v_2^2}{v^2} \gamma^5 \partial_\mu \theta' \right) \psi' \quad (16)$$

which can be obtained eliminating the CP violating phase θ_1 in Eq.(15) and after a hypercharge rotation transformation. Eq.(16) can mediate a non-local electroweak baryogenesis mechanism [30]. In fact, the Bubble wall propagating along a direction z with a velocity U

$$\mu_{\psi'} = \frac{U \log 2}{3\zeta(3)} \frac{v_2^2}{v^2} \partial_z \theta' \left(\frac{m_{\psi'}}{T'} \right)^2 \quad (17)$$

(where ζ is the Riemann function) sources the Boltzmann equation

$$\frac{dn_B}{dt} = -\frac{(\#_f)\Gamma(T')}{2T'} \sum_i \mu_i \quad (18)$$

where $\#_f$ is the number of families and μ_i are chemical potentials of LH fermions of species i . The Dark Baryon asymmetry can be calculated with the same methods used in Ref.[30]. We obtain the following result:

$$B' = \frac{n_{B'}}{s'} = C \frac{\eta}{D} \frac{45}{4g'_* \pi^4} U \left(\frac{m_f}{T'} \right)^2 \left(\frac{1}{2T' L_W} \right) \Delta \theta'_{CP} \quad (19)$$

where $g'^* = g_*(T')$, where C depends on various approximation regimes:

$$C = -\frac{\Gamma_s D_L}{U^2}, \quad U^2 > \Gamma_\tau D_R, \Gamma_s D_L$$

$$C = +\frac{2}{3} \frac{\Gamma_s D_R}{U^2}, \quad \Gamma_\tau D_R > U^2 > \Gamma_s D_L$$

$$C = +\frac{2}{3}, \quad \Gamma_\tau D_R, \Gamma_s D_R > U^2$$

$$C = -\frac{1}{2} \frac{U}{\sqrt{\Gamma_{ss} D_q}} \frac{3\Gamma_s D_q}{U^2}, \quad \frac{\delta D_q}{D_q} < \sqrt{\frac{U}{\Gamma_{ss} D_q}} < 1$$

$$C = -\frac{1}{2} \frac{\delta D_q}{D_q} \frac{3\Gamma_s D_q}{U^2}, \quad \frac{\delta D_q}{D_q} > 1 \quad U^2 > \Gamma_s D_q$$

where

$$D_L^{-1} = 8\alpha_W^2 (1 + 0.8 \tan^4 \theta_W) T' \simeq \frac{T'}{100}$$

$$D_R^{-1} \simeq 28\alpha_W^2 \tan^4 \theta_W T' \simeq \frac{T'}{380}$$

$$D_q^{-1} \simeq 8\alpha_s^2 T' \simeq \frac{T'}{6}$$

$$\Gamma_q = 0.2\alpha_s y_t^2, \quad \Gamma_{LR} = \Gamma_{\tau R} = 2\Gamma_{\tau L} = 0.3\alpha_W y_\tau^2$$

$$\Gamma_s = 6N_F \kappa_s \alpha_W^4 T' \simeq 2 \times 10^{-5} \kappa_s T'$$

$$\Gamma_{ss} = 64\kappa_{ss} \alpha_s^4 T' \simeq \kappa_{ss} \frac{T'}{40}$$

where L_W is the wall thickness, $D_{L,R,q}$ are diffusion coefficients of LH, RH particles and quarks, $\Gamma_{q,LR}$ perturbative decay rates in plasma mediated by Higgs bosons, $\kappa_{s,ss}$ are numerically estimated constants in the range $0.1 \div 1$, $y_{t,\tau}$ Yukawa couplings of top and τ and η is the persistent length of the initially injected particles currents.

The Cold Dark Matter coincidence $\Omega_{CDM} \simeq 5\Omega_B$ can be recovered from electroweak baryogenesis with the right choice of initial parameter conditions in Eq.(19).

An inevitable prediction of this scenario is that Bubbles inevitably will collide each other, producing gravitational waves. The frequency and intensity of the produced signal is controlled by the Dark SM couplings, Dark phase transition critical temperature, number of dark degree of freedoms g'^* , Bubbles velocity and Higgs potential shape.

In particular, we can estimate frequency and intensity using similar calculations of Refs.[31, 32] and more recently [33]. We obtain:

$$f_{Collisions} \simeq 5 \times c_i \left(\frac{\beta}{H_*} \right) \left(\frac{T'^*}{100 \text{ GeV}} \right) (g'_*)^{1/6} \text{ Hz} \quad (20)$$

$$\Omega_{Collisions} h^2 \simeq c_i \epsilon^2 \left(\frac{H_*}{\beta} \right)^2 \left(\frac{\alpha}{1+\alpha} \right) \left(\frac{U^3}{0.24 + U^3} \right) \left(\frac{100}{g'^*} \right)^{1/3} \quad (21)$$

U bubble velocity. Let us note that the case $T'_0 \geq T_0$ with T_0 temperature $\leq T_{BBN}$ is already excluded by BBN and CMB constraints on sterile neutrini. In fact,

$$\Delta N_\nu = 6.14 \left(\frac{T'_0}{T_0} \right)^4 \quad (22)$$

and, in order to have $\Delta N_\nu < 1$, $T'_0/T_0 \leq 0.64$. So that, the dark first order transition has necessary to cool the dark sector down to $T'_0 < 0.64 T_0$. Choosing $T' \simeq 0.5T$ asymmetric reheating mechanisms and various values of $\Lambda = 590, 600, 650 \text{ GeV}$, we show interesting examples of gravitational wave spectrum predicted by the dark electroweak phase transition in Fig.1. The discussion of a specific mechanism for a $T' \neq T$ is beyond the purposes of this letter. But it can be understood as an asymmetric reheating of the O- and D- sectors, i.e. the inflaton field is asymmetrically coupled to the two sectors. Of course an exactly Z_2 -symmetric lagrangian should guarantee democratic inflaton couplings with the two sectors. However, non-perturbative corrections can generating soft breaking corrections to inflaton couplings with the two sectors. In conclusions, we will comment on possible UV origin of extra terms. Finally, we show a concrete example of dark baryon production compatible with sterile neutrino limits: for $m_{f'}/T' \simeq y'_{f'} = y_f$, Eq.(19) is $g'_* U (y_f/L_W T')^2 \Delta\theta'_{CP}$, where L_W is the wall thickness; taking $\eta = 6Dv$, with $v = (1/4 \ln 2)(1/2 L_W T')$, $U > 2.1 y_\tau$; assuming $T' \sim 0.5T$, we find

$$\frac{n_{B'}}{s'} \simeq -\frac{8}{g'_*} \frac{y_\tau^2}{(L_W T')^2} \frac{\kappa_s}{U} \alpha_W^2 \Delta\theta'_{CP}$$

with $L_W T' \sim 20$, $g'_* \simeq 100$ and $U \simeq 0.1$ we obtain

$$\frac{n_{B'}}{s'} \sim -2.4 \times 10^{-10} \kappa_s \Delta\theta'_{CP}$$

which approximately must saturate five times the BBN bound $(4 \div 11) \times 10^{-11}$ in order to recover the coincidence $\Omega_{DM} \simeq 5\Omega_B$, i.e. implying large dark CP violation $\Delta\theta'_{CP} \sim 1$.

IV. CONCLUSIONS AND REMARKS

In this letter, we have explored the possibility to detect gravitational wave signals from a dark electroweak baryogenesis (DEB) of a dark standard model. DEB is one of the simplest classes of mechanisms explaining dark matter genesis from a dark standard model. It predicts the materialization of Bubbles and their collisions generate a characteristic gravitational spectrum detectable in the next generation of experiments like eLISA (C1) and U-DECIGO. As a consequence, gravitational wave astronomy can provide an important test for dark standard model, which is a good candidate of dark matter. Future data from gravitational waves experiments can provide important limits on dark sectors.

We have discussed the example of a dark non-local electroweak baryogenesis where CP-asymmetry introduced from a two Higgs model. On the other hand, in principle, our model can be embedded in a supersymmetric $G_{SM} \times G'_{SM} \times Z_2$. In this case, SUSY introduces extra CP-violating phases affecting the Baryogenesis mechanism. Supersymmetry can be asymmetrically broken among the two sectors by non-perturbative effects. It is possible that supersymmetry is broken at the electroweak scale or even at smaller scales in the dark sector, providing extra CP violating phase, while in our sector broken at higher scales. For example it is conceivable that SUSY could be dynamical broken by instantonic effects at high scales in our ordinary sector while gravitational or gauge mediators from the O-SM to D-SM transmit the SUSY breaking information. This mechanism naturally guarantees a hierarchy $M_{SUSY} \gg M'_{SUSY}$ where M_{SUSY}, M'_{SUSY} are susy breaking scales of O-DM and D-SM respectively. In this case, dark gravitinos or other SUSY particle can have a mass close upon the electroweak scale and in principle they can decay injecting extra neutrons or photons during dark BBN, completely changing the dark nuclei composition of the dark sector with respect to O-BBN⁴. On the other hand, our model can be UV completed in context intersecting D-brane parallel worlds. In this case, extra non-perturbative terms like H_1^6, H_2^6, \dots softly breaking the Z_2 symmetry can be generated by exotic E-brane instantons, similarly to mechanisms suggested in our recent papers in various contexts [37–40]⁵. As well, inflaton couplings with the O- and D- sectors are the same at perturbative level, while exotic instantons can generate soft Z_2 -breaking corrections leading to an asymmetric reheating of the O- and D- sectors ($T' \neq T$). Let us also remark that a dark standard model scenario weakly interacting with our ordinary sector is also strongly motivated by solutions of the hierarchy problem introducing N parallel sector and obtaining a low cutoff $\Lambda_{UV} \sim M_{Pl}/\sqrt{N}$ [42, 43]. We conclude remarking that searches for dark first order phase transitions with gravitational wave detectors are strongly motivated by dark matter genesis mechanisms such as dark electroweak baryogenesis in context of dark standard model dark matter (DSDM). This could be a new interesting paradigm in dark matter phenomenology from gravitational radiation.

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⁴ Limits on supersymmetric particles from BBN were firstly sug-

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gested in [36].

⁵ We suggest that it could be interesting to explore possible effects of non-local interaction terms in electroweak baryogenesis

in context of effective non-local quantum field theories like ones studied in Refs.[41] and embedding the SM of particles.